

AD-A274 993

②

WL-TR-93-005



100kA, 5000 V Solid State Opening Switch for Inductive Energy Stores

Mark W. Heyse, Joshua Kolawola, Nolan E. Taconi, Jr.

**Wright Laboratory, Armament Directorate
Weapon Flight Mechanics Division
Aerodynamics Branch
Eglin AFB FL 32542-6810**

Ed E. Bowles, W.G. Homeyer, John M. Rawls

**General Atomics
P.O. Box 85608
San Diego CA 92138**

**DTIC
ELECTE
JAN 25 1994
S B D**

DECEMBER 1993

FINAL REPORT FOR PERIOD APRIL 1990 - MAY 1993

Approved for public release; distribution is unlimited.

**WRIGHT LABORATORY, ARMAMENT DIRECTORATE
Air Force Materiel Command - United States Air Force - Eglin Air Force Base**

94-02091



94 1 24 056

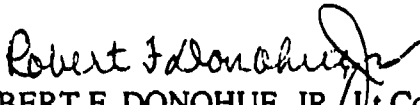
NOTICE

When government drawings, specifications, or other data are used for any purpose other than in connection with a definitely government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner construed, as licensing the holder or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This technical paper has been reviewed and is approved for publication.

The Public Affairs Office has reviewed this paper and it is releasable to the National Technical Information Service (NTIS), where it will be available to the general public, including foreign nationals.

FOR THE COMMANDER


ROBERT F. DONOHUE, JR., Lt Col, USAF
Chief, Weapon Flight Mechanics Division

Even though this paper may contain special release rights held by the controlling office, please do not request copies from the Wright Laboratory, Armament Directorate. If you qualify as a recipient, release approval will be obtained from the originating activity by DTIC. Address your request for additional copies to:

Defense Technical Information Center
Cameron Station
Alexandria VA 22304-6145

If your address has changed, if you wish to be removed from our mailing list, or if your organization no longer employs the addressee, please notify WL/MNAA, 101 W EGLIN BLVD STE 346A, EGLIN AFB FL 32542-6810, to help us maintain a current mailing list.

Do not return copies of this paper unless contractual obligations or notice on a specific document requires that it be returned.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to: Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE Dec 93	3. REPORT TYPE AND DATES COVERED Technical Paper, Apr 90 - May 93		
4. TITLE AND SUBTITLE 100kA, 5000V Solid-State Opening Switch for Inductive Energy Storage		5. FUNDING NUMBERS C: F08635-90-C-0241 PE: 63217C PR: 1203 TA: 04 WU: 21		
6. AUTHOR(S) Mark W. Heyse, Joshua Kolawole, Nolan E. Taconi, Jr., and Ed E. Bowles				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) General Atomics P.O. Box 85608 San Diego CA 92138		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Wright Laboratory, Armament Directorate Weapon Flight Mechanics Division Aerodynamics Branch Eglin AFB FL 32542-6810		10. SPONSORING/MONITORING AGENCY REPORT NUMBER WL-TP-93-005		
11. SUPPLEMENTARY NOTES Approved by PA in May 1993 for unlimited release. Published in the 9th IEEE Pulse Power Conference proceedings.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; DISTRIBUTION IS UNLIMITED		12b. DISTRIBUTION CODE A		
13. ABSTRACT (Maximum 200 words) Inductive energy stores have demonstrated higher energy storage densities than capacitive energy stores. A limitation in the use of inductive energy stores has been the availability of adequately rated opening switches. A self commutated solid-state switch has been developed for use as an opening device for an inductive energy store. The switch is rated at 100kA and 5000V and is composed of four identical 25kA switch modules. The charging pulse lengths for the intended application vary from 0.1 to 5 seconds. Efficiency and volumetric power density were optimized. The switch topology is a two stage hybrid consisting of an SCR-FET/SCR-IGBT combination. The switch is designed to charge an inductive energy store and repetitively commute the current into a railgun load. A 100kA switch module has been built and successfully tested. The theory of operation, circuit topology and test results are given in this paper.				
14. SUBJECT TERMS Railguns, Electromagnetic Launcher, Solid-State Switch, Electromagnetic Accelerator, Opening Switch		15. NUMBER OF PAGES 11		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR	

THIS PAGE INTENTIONALLY LEFT BLANK

PREFACE

This paper documents research conducted on a solid-state opening switch for inductive energy store and was presented at the 9th IEEE Pulse Power Conference in Albuquerque NM on 21 Jun 93.

This work was funded by WL/MNAA of the Armament Directorate at Eglin AFB FL under the Kinetic Energy Weapons Program of the Strategic Defense Initiative. Mr. Mark W. Heyse from WL/MNAA, Dr. Joshua Kowawole from SAIC, and Mr. Ed Bowles from General Atomics, Inc. in San Diego CA performed the work during the period of Apr 90 to Dec 93 at Eglin AFB FL.

DTIC QUALITY INSPECTED 5

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

THIS PAGE INTENTIONALLY LEFT BLANK

A 100 kA, 5000 V SOLID STATE OPENING SWITCH FOR RAILGUN APPLICATIONS

E. E. Bowles
General Atomics San Diego, Calif. 92186

M. W. Heyse, J. Kolawole, and N. E. Taconi Jr.
Wright Laboratory Eglin Air Force Base, Fl. 32542

Abstract

Abstract - Inductive energy stores have demonstrated higher energy storage densities than capacitive energy stores. A limitation in the use of inductive energy stores has been the availability of adequately rated opening switches. A self commutated solid state switch has been developed for use as an opening device for an inductive energy store. The switch is rated at 100 kA and 5000 V and is composed of four identical 25 kA switch modules. The opening repetition rate for the intended application varies from single pulse to 10 Hz. Efficiency and volumetric power density are optimized. The switch topology is a two stage hybrid consisting of an SCR-FET / SCR-IGBT combination. The switch is designed to charge an inductive energy store and repetitively commute the current into a railgun load. A 100 kA switch module has been built and successfully tested. The theory of operation, circuit topology and test results are given in this paper.

Introduction

Railgun research requires current pulses in the hundreds of kiloamps delivered at thousands of volts. Typically a capacitive energy store and a closing switch are used to deliver this power to the load. High power closing switches are available in the form of sparkgaps, ignitrons, and SCRs [1]. Each of these devices can momentarily conduct currents in excess of 100 kA, but once turned on they cannot interrupt current flow.

Another method to energize a railgun is with an inductive energy store and an opening switch. Opening switches for inductive energy stores must close and conduct current to charge the energy store and then momentarily open (interrupt the current flow) and commute (transfer) the current to the load. Mechanical switches, GTO thyristors[2], and transistors are available for this opening switch duty but all have much lower power densities than closing switches.

Solid state devices are generally preferred over other switch types if a performance match is available for the intended duty. The purpose of this program is to build and demonstrate a solid state opening switch that has sufficiently low conduction losses and sufficiently high power ratings to be practical in inductive energy store railgun application. This paper describes the design and testing of a solid state opening switch that meets those goals.

Theory of operation

Figure 1 shows a circuit schematic for the demonstration switch. It can be seen that the switch is of a hybrid design with two conduction paths and four active switching elements.

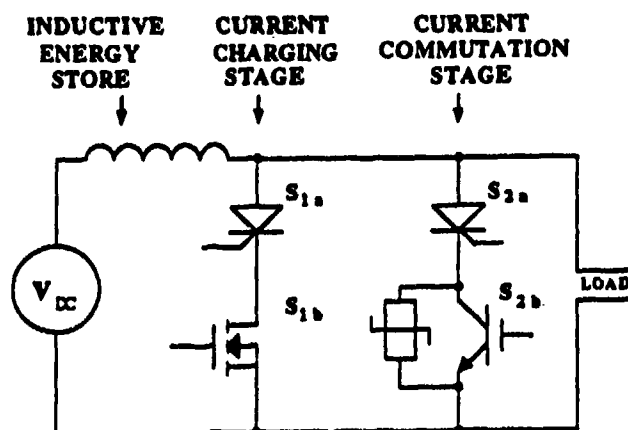


Fig. 1. Opening switch circuit schematic.

As will be explained, the different switching elements of the circuit schematic pertain to the different switching phases that an inductive energy store opening switch must support.

These phases are:

- 1) **Charge**
Close and conduct inductor current from zero to maximum with minimum losses. This requires low conduction voltage drop.
- 2) **Commutation**
Upon command, commute current out of the switch and into the railgun load by forcing a large voltage drop across the switch. This requires high commutation voltage and fast turn-off speed.
- 3) **Voltage Blocking**
Block any voltage produced by the dynamic railgun load and maintain zero current in the switch. This requires high blocking voltage in the off state.

4) Reclosure

Reclose and recover current from the load upon command. This requires fast turn-on speed.

These requirements have spawned the dual stage hybrid switch design shown in figure 1. The two conduction paths, S_1 and S_2 in Fig. 1, provide for two separate switching stages. Stage 1 (switch S_1) provides for the low loss charging function of the switch while stage 2 (switch S_2) provides for the forced current commutation out of the switch. Providing these two stages has allowed the switch to meet the conflicting design requirements of low conduction loss during charging and a fast, high voltage current commutation to the load.

The topology also provides for a cascode (series) connection of an SCR and a transistor in each switch stage. The charging switch stage has a 5000 V. SCR in cascode with a 50 V. FET transistor while the commutation switch stage has a 5000 V. SCR in cascode with a 1000 V IGBT transistor. This arrangement of semiconductor devices allows the transistors to accomplish the lower voltage commutation functions while the SCR accomplishes the 5000 V blocking function with a single series device. By separating the functions of charging, commutating, and voltage blocking we have been able to provide a switch that compromises few performance attributes and has a power density approaching that of a closing switch (SCR).

Since two MOS devices (FET, IGBT) control an SCR thyristor, we call the switch a Bi-MOS Thyristor (BMT).

Operational Description

To see how this concept works, refer to the circuit schematic in Fig. 1 and the switching timeline that depicts the intended current and voltage waveforms in Fig. 2. Switches S_{1a} and S_{1b} are the charging switches. Initially, the combined switch must hold off the relatively low source voltage. Both switches S_{1a} and S_{1b} are triggered into conduction to initiate the charge cycle.

When the desired current is reached and one wishes to begin the commutation process, switch S_{2a} and S_{2b} are triggered into conduction while the FET switch S_{1b} is given a gate command to increase its resistance until a 40 V drop is obtained across its terminals. This 40 V drop will commutate current out of switch S_1 , and into switch S_2 at a rate determined by the self inductance of the switch S_1 - S_2 circuit. After current falls to zero in switch S_1 the SCR (S_{1a}) will begin to recover its voltage holding capabilities. The recovery time, t_q , is 275 μ s for the 5000 V SCR we have chosen. After $\geq 275 \mu$ s of full current conduction the commutation switch, switch S_{1b} , is given a gate command to turn off. This command initiates the commutation of current from the switch to the load. The time for this commutation is determined by the inductance of switch S_2 and the load circuit and the voltage produced across switch S_2 .

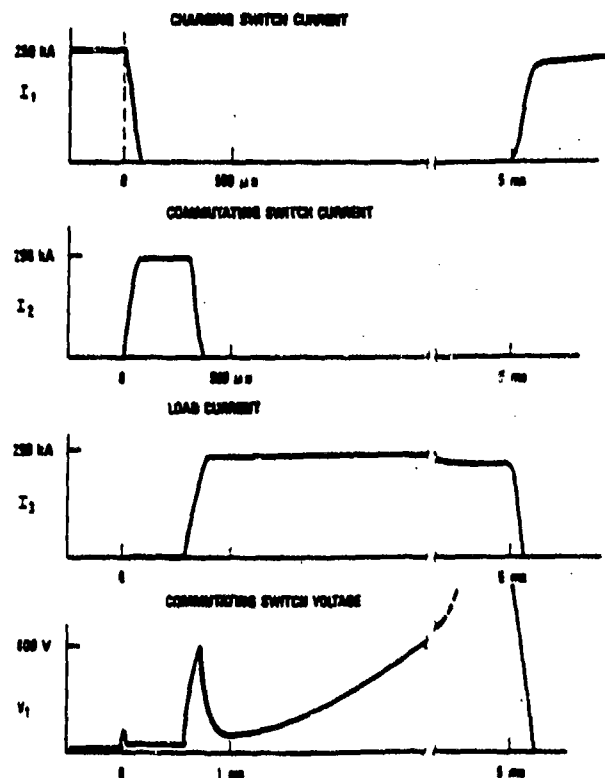


Fig. 2. Switching timeline for opening switch.

The IGBT switch S_{2b} has a 1000 V rating and an 800 V MOV clamp across it. An IGBT turn-off time of 10 μ s is selected to provide a smooth current hand off to the MOV clamp, to maintain a reapplied dV/dt to the S_{1a} SCR of ≤ 100 V/ μ s, and to minimize switch S_{2b} turn-off loss.

After the IGBT of S_{2b} is fully turned off, the MOVs maintain 800 V across its terminals until current is fully commutated to the load. With nominal circuit inductances this turn off process takes $\sim 75 \mu$ s. The entire process takes < 1 ms, allowing switch S_2 to be pulse rated.

After commutation is complete, the voltage across the switch will fall to a level dictated by the instantaneous voltage drop of the load (this voltage is generally about 200 V and much less than the 1000 V rating of S_{2b}). The commutation switch SCR, S_{2a} , is allowed recovery time in the interval between current commutation and the point where the dynamic voltage produced by the load exceeds 800 V (speed voltage). After this recovery time elapses, $\sim 250 \mu$ s for SCR S_{2a} , the entire switch is ready to support a 5000 V back voltage that will eventually be produced by the accelerating railgun projectile.

Circuit description

A photograph of the first 25 kA, 5000 V switch module is shown in Fig. 3. Four of these modules composing a 100 kA switch is shown in Fig. 4. This 100 kA switch was first tested at Eglin AFB in July, 1992.

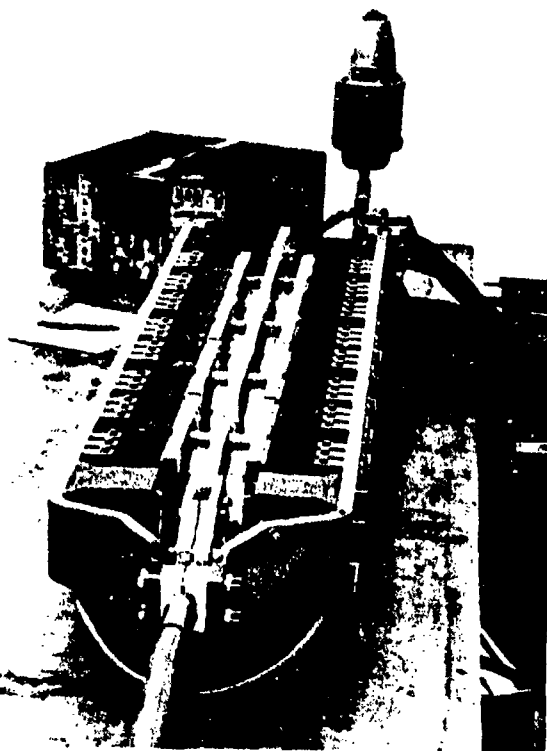


Fig. 3. Photograph of 25 kA switch module.

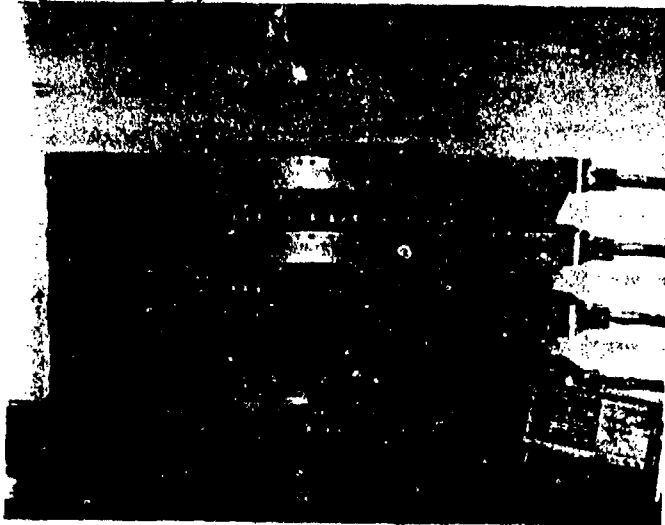


Fig. 4. Photograph of 100 kA, 5000 V opening switch.

In order to achieve a 25 kA module rating several submodules were placed in parallel. A charging switch submodule consists of an ABB CS-2104 [3], 5000 V, SCR in cascode connection with two FET modules. A photograph of a single switch submodule is shown in Fig. 5.

Each FET module (the two black boxes in Fig. 5) consists of an array 50 V FET transistors in parallel connection. The nominal 5 second current rating for each charging switch submodule is 4,166 A at a 2.2 V conduction drop. Six conduction switch submodules are placed in parallel to achieve the 25 kA rating.

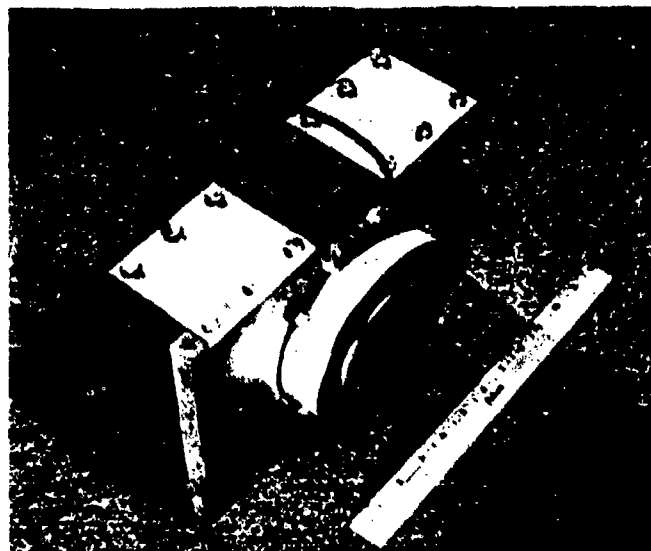


Fig. 5. Single 4,166 A switch submodule showing SCR, heat sink, and FET transistors.

A commutation switch submodule uses the same SCR as a conduction switch submodule and is identical in appearance. The only difference is the use of 1000 V IGBTs in each of the two cascode transistor modules. An IGBT transistor module and its associated control circuitry is shown in Fig. 6.

This 1000 V IGBT transistor array uses 16 large format IGBT chips manufactured by Advanced Power Technologies.

The nominal current rating for each commutation switch submodule is 12,500 A at a 7.0 V drop for operation ≤ 3 ms for each opening cycle. Two commutation switch submodules are placed in parallel to achieve the 25 kA rating.

To complete the switch, seven Siemens B80K275 100 mm, zinc-oxide varistors are placed across the IGBT transistors in the commutation switch submodule. Each MOV can absorb up to 4100 Joules of commutation energy. The current dependent voltage clamping action of these MOVs can be seen in Fig. 8.

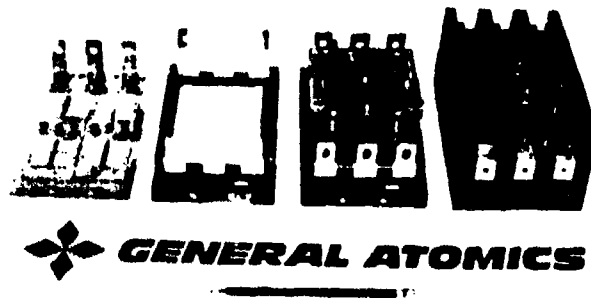


Fig. 6. A full transistor module and its associated control circuitry.

Test Results

The 100 kA switch module has been successfully operated at full current and repetition rate at Eglin Air Force Base. The switch, as installed in its test setup, is shown in Fig. 7. Referring to Fig. 7, the battery power supply and 40 μ H inductor are shown on the left of the switch while the railgun and dummy load are shown on the right. Current and voltage waveforms during a 103 kA commutation into a dummy load are shown in Fig. 8.

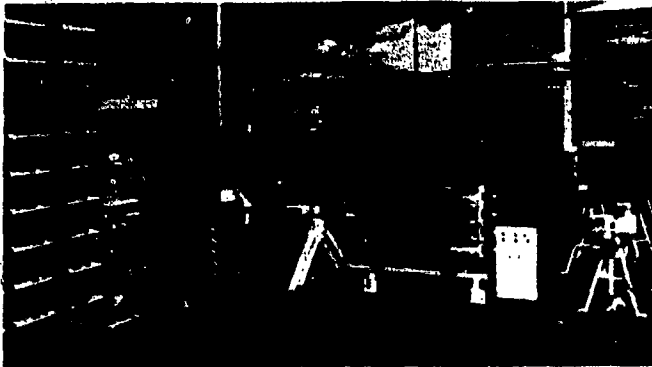


Fig. 7. Test setup at Eglin Air Force Base. Battery power supply, storage inductor, switch, and railgun can be seen.

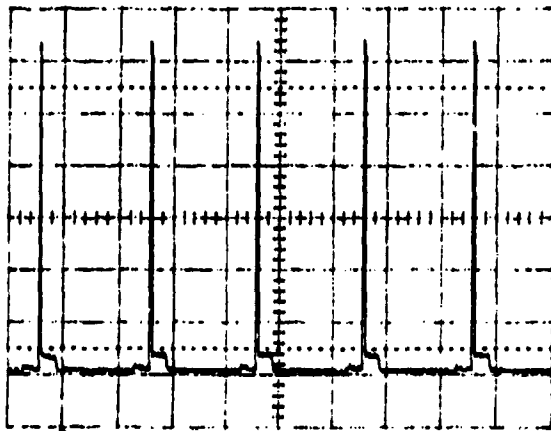


Fig. 8. Operational test results from 103 kA current commutation, into a dummy load at 5 Hz. The voltage waveform from five commutation events are windowed at a time base of 1 ms/div and an ordinate of 100 V/div (intervening 200 ms between shots is not shown). First voltage rise, ~ 10V, is switch S1 to S2 commutation. Second voltage spike, ~ 640 V, is the commutation from switch S2 to the load. Voltage plateau after the voltage spike is the resistive voltage drop of the dummy load. All 103 kA is commutated to the load when this ~ 50V plateau is reached.

Conclusion

A hybrid arrangement of power semiconductor that consists of an SCR-FET / SCR-IGBT combination has been designed and built for use as an inductive energy store opening switch. Exceptional performance has been obtained

with a 100 kA, 5000 V switch module using this switching topology. The switch can operate at full current at up to a 50 Hz rate.

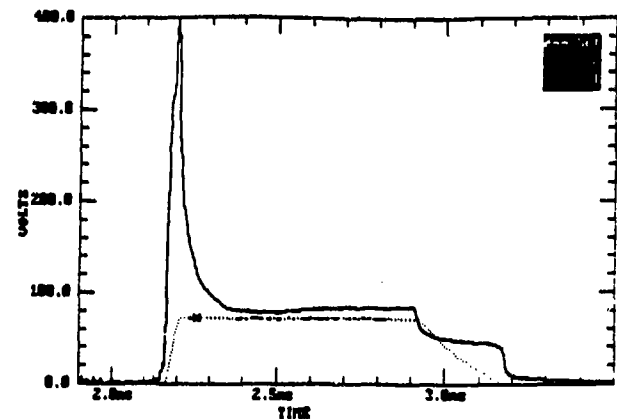


Fig. 9. Operational test results from an 83 kA, 5 Hz, 5 shot railgun burst. The waveform shows the commutation voltage and current from the first shot. Data set 1 is railgun current, data set 2 is railgun breech voltage. Switch reclosure occurs at 2.9 ms.

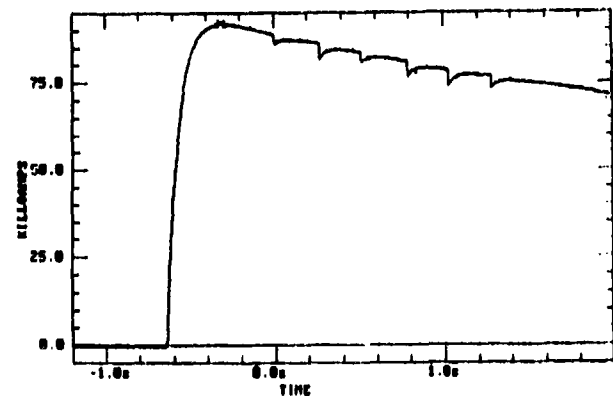


Fig. 10. Storage inductor current during 92 kA, 4 Hz, 6 shot railgun burst. Current is approximately constant, apparent droop is caused by Rogowski current monitor integrator.

References

1. E. Spahn, et al., "The Use of Thyristors as Main Switches in EML Applications", Proceeding of the Sixth (6th) Electromagnetic Launch Technology Symposium, April, 1992, Austin TX.
2. T. F. Podlesak, J. A. McMurray, J. L. Carter, "Demonstration of a Compact Solid Opening and Closing Switch Utilizing GTO's in Series", Proceeding of the 1990 IEEE Power Modulator Symposium, June, 1990, San Diego Ca, pp 371-374.
3. J. Vitins, J. Steiner J. Welleman, "High Power Semiconductors for Pulsed Switching", Proceeding of the Seventh (7th) IEEE Pulsed Power Conference, June 1989, Monterey, Ca, pp 352-357.

Distribution
01 DEC 93

Defense Tech Info Center
Attn: DTIC-DDAC
Cameron Station
Alexandria VA 22304-6145
2

Eglin AFB FL 32542-5000

WL/CA-N 1
WL/MNOI (Tech Library) 1
WL/MNSH 4
WL/MNS 1

DARPA/TTO
Tactical Technology Office
Attn: Dr. Peter Kemmy
1400 Wilson Blvd.
Arlington VA 22209-2308
1

U.S. Army Strategic Defense Command
Attn: DASD-H-Q (Lt Col Steven Kee)
P.O. Box 1500
Huntsville AL 35807-3801
1

Naval Surface Weapons Center
Attn: Mr. P.T. Adams, Code G-35
Dahlgren VA 22448
1

U.S. Army Strategic Defense Command
Attn: CSSD-AT-E (Mr. Dimitrios Lianos)
P.O. Box 1500
Huntsville AL 35807-3801
1

Office of Naval Research
Attn: Code 1132P (Dr. Gabriel Roy)
800 N. Quincy Street
Arlington, VA 22217-5000
1

U.S. Army, ARDEC
SMCAR-FSE, Bldg 329
Attn: Mr. Tom Coradeschi and
Dr. Thaddeus Gora
Picatinny Arsenal NJ 07806-5000
1

HQ DNA
Attn: OTA (Mr. D. Lewis & Mr.A. Fahey)
6801 Telegraph Rd
Alexandria VA 22310-3398
1

U.S. Army Ballistic Research Laboratory
SLCBR-TB-EP
Attn: Dr. John Powell & Mr. Alex Zielinski
Aberdeen Proving Ground MD 21005
1

SDIO/TNC
Attn: Mr. Mick Blackledge
Washington DC 20301-7100
1

WL/POOC
Attn: Dr. Alan Garscadden
Wright-Patterson AFB OH 45433-6553 1

SDIO/TNI
Attn: Dr. Dwight Duston and
Lt Col Pedro Rustan
Washington DC 20301-7100
1

AFOSR
Attn: AFOSR/NR (Dr. Barker)
Bolling AFB, DC 20332-6448
1

HQ USAF
Attn: SAF/AQT (Mr. Michael Flynn)
The Pentagon, Room BE939
Washington DC 20330-5425
1

Auburn Research Foundation
Office of the Vice Pres for Research
Attn: Ms. Barbara Ausharian
202 Samford Hall
Auburn University AL 36849-5112
DAL: 29335; CCAL: 0001689
1
Route to Dr. R.F. Askew (Dir, Leach
Nuclear Science Ctr) and Dr. E.J. Clothiaux
(Dept of Physics)

Institute for Advanced Technology
The University of Texas at Austin
Attn: Dr. Harry D. Fair
4030-2 West Braker Lane, Suite 200
Austin, Texas 78759
DAL: 32292; CCAL: 0018582
1

IAP Research, Inc.
Attn: Mr. David P. Bauer
2763 Culver Ave
Dayton OH 45429-3723
DAL: 28548; CCAL: 0000927
1
Route to Dr. John P. Barber

Lawrence Livermore Nat'l Lab
Attn: Ms. Jean Higby
P.O. Box 808
Livermore CA 94550
DAL: 06635; CCAL: 0001362
1
Route to Dr. Ron Hawke

Los Alamos National Laboratory
Attn: Jack Carter, Report Librarian
Dr. Jerald V. Parker
P. O. Box 1633, MS-P364
Los Alamos NM 87545
DAL: 31455; CCAL: 0015790
1
Route to Ms. Helen Bustus
Classified Custodian

Maxwell Laboratories
Attn: Ms. Linda N. Thomas
8888 Balboa
San Diego CA 92123
DAL: 19248; CCAL: 0001705
1
Route to Dr. Ian McNab

GA Technologies, Inc.
Attn: Mr. Charles N. Stem
P.O. Box 85608
San Diego CA 92138
DAL: 06785; CCAL: 0002129
1
Route to Mr. John Rawls

General Research Corporation
Attn: Ms. Carol Donner
P.O. Box 6770
Santa Barbara CA 93160-6770
DAL: 10824; CCAL: 0000358
1
Route to Dr. William Isbell

SAIC Advanced Concepts Division
Attn: Ms. Bethany Madden
1519 Johnson Ferry Rd., Suite 300
Marietta GA 30062
DAL: 32383; CCAL: 0009775
1
Route to Dr. Jad Batteh

SAIC
Attn: Mrs. Susan Deonaraine
1427 N. Eglin Parkway
Shalimar FL 32547
DAL: 31327; CCAL: 0011312
1
Route to Dr. Keith Jamison

Sandia National Laboratory
Attn: Technical Library
P. O. Box 5800
Albuquerque NM 87185
DAL: 23683; CCAL: 0001104
1
Route to Mr. Arthur Gurnther (Dept 0450)

University of Texas
Center for Electromagnetic
Balcones Research Center
Attn: Ms. Marcie Powell
P.O. Box 200668
Austin TX 78720-0668
DAL: 00111; CCAL: 0005531
1
Route to Prof William Weldon and
Mr. Raymond Zowarka

SPARTA

Attn: Ms. Maxine Fahlbusch
9455 Towne Centre Dr
San Diego CA 92121-1964
DAL: 28397; CCAL: 0001185

1

Route to Mr. Stuart Rosenwasser

System Planning Corporation
Attn: Ms. Phyllis W. Moon
1500 Wilson Blvd.
Arlington VA 22209
DAL: 20874; CCAL: 0000279

1

Route to Mr. Donald E. Shaw

University of Tennessee
Space Inst/Library
Attn: Ms. Marjorie Joseph
Tullahoma TN 37388-8897
DAL: 15965; CCAL: 0000429

1

Route to Dr. Dennis Keefer

Westinghouse Elec. Corp, Marine Div.
Technical Library EE-5

Attn: Riet Blei

P.O. Box 3499

Sunnyvale CA 94088-3499

DAL: 06933; CCAL: 0000703

1

Route to Mr. Hugh Calvin

Parker Kinetic Designs
Attn: Mr. Cliff Drummond
Mr. Jim Weldon
8303 Mopac, Suite 240C
Austin, TX 78759
DAL: 32769; CCAL: 0002456